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Challenges of decarbonizing global maritime container shipping toward net-zero emissions

Bo Lu¹, Xi Ming², Hongman Lu¹, Deyang Chen³ and Hongbo Duan²✉

Responsible for the most significant part of the world's burning of marine fossil fuels and shipping emissions, global maritime container shipping is under decarbonization pressure. This paper develops an integrated framework of bottom-up emission estimation and upscaling pathway analysis (BEEPA) to measure global maritime container shipping emissions from 2015 to 2020, and project possible pathways toward carbon neutrality by designing typical decarbonization scenarios. The result shows that global total seaborne container emissions fluctuated from 2015 to 2020 with a maximum value of 264 Mt, and the average annual energy consumption is 77.7 Mt (heavy fuel oil-equivalent). Container traffic to/from Asian ports generate the largest volumes of shipping emissions, accounting for about 55% of the global total. Under the most stringent scenario, container shipping emissions peak in 2025 and then quickly decline to 19.6 Mt in 2050, nearing the International Maritime Organization's goal of reaching net zero emissions by or around 2050. Energy efficiency improvements contribute to emission reduction in the near term, but the trade growth impact still predominates in the shipping emission increase. With the maturity of infrastructural development and technological innovation, the energy transition would be the largest contributor emission reductions over the medium to long term.

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INTRODUCTION

Accounting for about 30% of global maritime CO₂ emissions, container ships are the most significant contributor to global maritime emissions^{1–4}. Emissions generated by maritime shipping can spread from oceans to land through atmospheric motion and adversely impact urban climate and human health^{5–8}. Without new emission control measures in the coming decades, the total maritime shipping emissions can reach up to 1500 Mt in 2050, representing an increase of 50% over 2018¹. To comply with the goal of the Paris Agreement, IMO approved a greenhouse gas (GHG) emission reduction strategy in 2018, reducing total maritime shipping emissions by at least 50% by 2050 compared to 2008⁹, and the ambition of the IMO are further strengthened in the 80th Marine Environment Protection Committee (MEPC 80) to peak GHG emissions from international shipping as soon as possible and to reach net-zero GHG emissions by or around 2050, considering different national circumstances¹⁰. 22 countries signed Clydebank Declaration for green shipping corridors, committing to establish at least six green shipping corridors between two or more ports worldwide by 2025, and more green shipping corridors will be included by 2030 to further decarbonize the shipping industry by 2050¹¹. Many container lines have set 2030 targets. For example, Maersk has set ambitious targets to achieve net-zero emissions by 2040¹². Multiple measures, such as strengthening energy efficiency regulations for new ships, encouraging ports collaborations to adopt emission abatement measures, establishing multi-donor trust funds for GHG emission reductions from ships¹³, etc., has been pushed out to support the carbon mitigation target. However, those measures do not align with current climate target, and pathways to achieve the international carbon reduction target are still unclear^{14,15}.

Due to the importance of container shipping, it is rather difficult to reduce container shipping activities. From 1980 to 2020, the

international trade carried by container ships surged from 0.1 billion tons to 1.85 billion tons. While it only makes up about 16% of the volumes carried by maritime shipping, container shipping accounts for more than half of the value carried¹⁶. At the same time, the capacity of global container ships also increased. The deadweight tonnage of container ships witnessed a surge from 10 million tonnage in 1980 to 225 million tonnage in 2020¹⁷. Container port traffic in 2021 is 1.7 times that of 2000, reaching 840,635 billion 20-foot equivalent unit (TEU)¹⁸. With the consistent increase in the need for international containerized transportation, fuel consumption and carbon emissions from container shipping will inevitably rise. Substantial mitigation are therefore urgently required to meet the marine emission reduction target.

Obtaining high spatial and temporal resolution shipping emission inventories is challenging due to the large scale and dispersion of global shipping activities. Automatic Identification System (AIS) data that shows advantages in tracking ship activities, has been largely used in previous studies to build high-precision emission inventories^{1–6,19,20}. Still, there are some problems in shipping emission estimation. Firstly, AIS data is discontinuous, and ship trajectories are therefore generated from a number of discrete data points. In some cases, such as bad weather, offshore congestion, and incorrect manual input of departure and destination, errors or omissions in AIS data are inevitable²¹, which may result in incorrect acquisition of ship trajectories and impact the accuracy and the efficiency of shipping emission estimation^{4,21}. Second, duplicate data resulting from weather disturbances, ocean hazards, and many other factors cannot be identified in the AIS, yielding the overestimation of shipping emissions⁵. What's more, it is difficult to use AIS data to distinguish service lines between countries with narrow waters²². Given the above limitations, many AIS-based estimations of shipping emissions are restricted to a single year or primarily focus on

¹School of Economics and Management, Dalian University of Technology, Dalian 116024, China. ²School of Economics and Management, University of Chinese Academy of Sciences, 100190 Beijing, China. ³Sino-Danish College, University of Chinese Academy of Sciences, 100190 Beijing, China. ✉email: hbduan@ucas.ac.cn

specific regions or nations^{23,24}. Few studies examine the multi-year trend of global container shipping emissions.

At present, global container shipping is mainly operated in the form of liner shipping. Liner shipping service data can illustrate the trade relationships between ports around the world, clearly describing the departure and destination of container ships during a voyage, and can provide better efficiency in calculating container ships' emissions²⁵. In addition, liner shipping service data ensures a high degree of relevance to global seaborne trade, since liner shipping is recognized as one of the cheapest means of delivering products and liners are structured in such a manner that hazardous materials and dangerous commodities may be securely transported. The use of liner shipping service route data helps to better understand shipping emissions embodied in trade flows between different regions or countries, and to propose emission reduction measures from the perspective of improving trade structure²⁵. On this basis, this paper tries to estimate container shipping emissions based on liner shipping service route data.

Existing research incorporates broad estimates of global shipping emissions and decarbonization paths^{26–29}, by considering the roles of international trade^{30,31}, vessel design³², or alternative fuels³³. An adequate and effective decarbonization program needs to be designed by combining bottom-up estimates of shipping emissions with key factors within the comprehensive socio-economic system. The fourth report of IMO estimates carbon emissions from the shipping industry until 2050 using long-term socio-economic projections¹, and Balcombe et al. (2019)¹⁴ assessed the combined potential for decarbonization of international shipping from a technical, environmental and policy perspective. Few studies, however, build such a framework, particularly simultaneously taking economic trade growth, energy efficiency improvements²⁹, fuel transition, and negative emission technologies into account. Thus, identification of the short-, medium- and long-term emission reduction challenges are imperative to attain the IMO's and the Paris climate targets.

This paper fills previous research gaps by constructing an integrated framework of bottom-up emission estimation and upscaling pathway analysis (BEEPA). It helps identify regions with the most potential for carbon reduction and the main factors influencing the changing trend of seaborne container shipping emissions. This paper also informs decarbonization pathways of global container shipping department toward 2050, given the uncertainties of trade growth and technological change, which can support the formulation and follow-up of energy transition and mitigation strategies in medium-to-long term. Most importantly, by exploring the drivers of emission changes at different terms, we clarify the mitigation strategies at different stages and facilitate shipowners' and ship managers' investment decisions on greener ships and technology.

RESULTS

Estimating emissions of global maritime container shipping

The total emissions derived by BEEPA method consist of two parts, emissions at sea (i.e., emissions produced during cruising mode) and emissions in port (i.e., emissions produced during port operations), and the detailed description of the BEEPA is illustrated in Method. As displayed in Fig. 1a, global total seaborne container emissions showed fluctuations from 2015 to 2020. There was a plummet from 252.9 Mt in 2015 to 227.1 Mt in 2016, and total emissions reached the peak in 2017 with a maximum value of 264 Mt. It decreased to the minimum of 226 Mt in 2018, and after that, emissions increased slightly in 2020. The trends of container shipping energy consumption and carbon emissions are basically the same (Fig. 1b). On the one hand, this reflects the existing unclean energy mix, with HFO and marine diesel fuel (MDO) being the primary energy sources used; on the other hand, trade fluctuations heavily affect energy consumption patterns. With the container shipping industry suffering a market downturn in 2016, the global container shipping demand increased by 6.4%

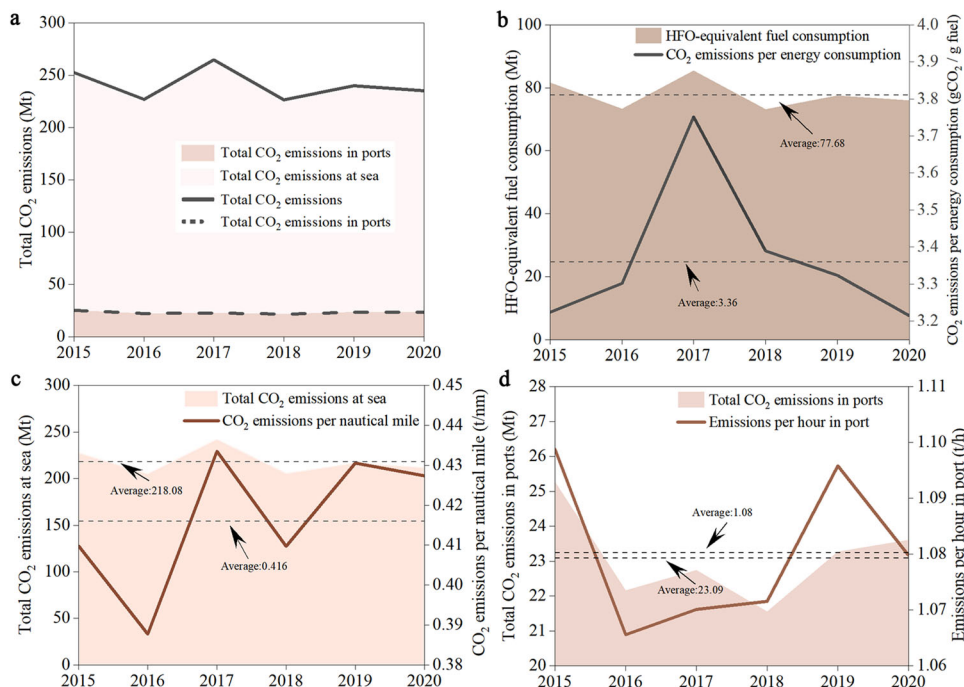


Fig. 1 Estimations of global maritime container shipping emissions and energy consumption. **a** Total CO₂ emissions depicting global maritime container shipping emissions produced in both cruising mode and port operations. **b** HFO-equivalent fuel consumption and CO₂ emissions per unit of energy consumption. **c** Total CO₂ emissions and CO₂ emissions per nautical mile during cruising mode. **d** Total CO₂ emissions and hourly CO₂ emissions produced during port operations. Dash lines in each subfigure show annual averages of carbon emissions from 2015 to 2020.

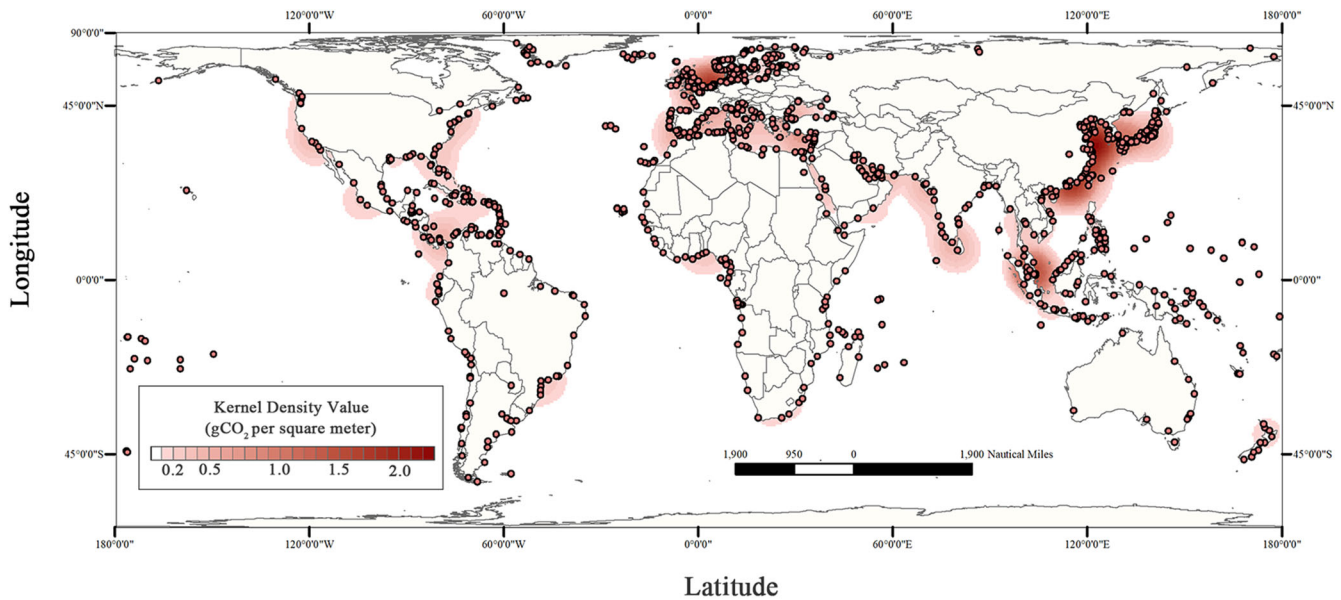


Fig. 2 Geographical distribution of container ships' emissions during port operations in 2020. The diagram illustrates the geographical distribution of global maritime container shipping emissions produced during port operations. Shipping emissions can be diffused, and there are some meteorological methods (e.g., Gaussian dispersion models) that can give detailed dispersion paths of emissions based on specific atmospheric conditions³⁹. For simplicity, this paper uses kernel density analysis to simulate the diffusion effect of shipping emissions produced during port operations. This is the reason why the emissions appear outside the port in this diagram.

in 2017; while the growth rate of seaborne trade slowed in 2018 mainly due to global economic uncertainty and geopolitical turmoil³⁴, which significantly impact container shipping energy consumption.

Global container shipping emissions generated during cruising mode account for the major part of the total emissions, and the annual average of this part is 218.1 Mt. What is notable is the increase in emissions per nautical mile during ocean cruising (see Fig. 1c). In recent years, influenced by factors such as geopolitics, populism, and the pandemic, international trade patterns have significantly changed. Regionalization has become the mainstream in many areas, promoting trade with nearby countries while reducing trade with countries outside certain regions. In Asia, for example, affected by the shipping market downturn and trade protectionism, the number of intercontinental services has decreased. The decentralized production process within Asia and the development of planned initiatives such as the Belt and Road Initiative, the Partnership for Quality Infrastructure, and the Regional Comprehensive Economic Partnership, have enabled intra-Asian containerized trade to maintain a stable expansion from 2015 to 2020. As global container ships' transport distance decreases, emissions per nautical mile during cruising will increase. The result suggests that under the situation of trade liberalization and regionalization, reasonable adjustment of trade structure and improvement of ship efficiency are essential measures to strike the balance between economic benefits and environmental benefits in the shipping industry^{34,35}.

Hourly emissions during port operations showed a surge between 2016 and 2019 and decreased from 2019 to 2020, with an annual average of 1.08 tons per hour. The mismatch between port capacity and surging operational demand results in increasing handling time^{36,37}. On average, for every 1% increase in container ship size, berthing time increases by nearly 2.9%³⁶. The operational inefficiency thereby leads to an increase in emissions, posing great air pollution and health threats to port cities and even regions hundreds of kilometers away from the ports^{5,33,38}. With the improvement of port capacity and development of digitalization, the pressure of port operation caused by surging operating volume is alleviated. Coupled with a slower growth rate

in shipping demand between 2019 and 2020, CO₂ emissions per hour during port operations from containerships have decreased^{31,36,37,39,40}. Due to port congestion, ships spend a lot of time in port or at anchor during the pandemic⁴¹, which explains the fact that emissions from anchorages grow. This partially compensates carbon emission reductions caused by the drop in shipping activities as a result of global lockdown measures⁴².

Geographical distribution of global container shipping emissions

As illustrated in Fig. 2, ports with the most significant container shipping emissions concentrated in Northeast Asia, Southeast Asia, the Malacca Sea, the Red Sea, the Mediterranean Sea, and the North Sea. China and the United States are the world's two largest producers of container shipping emissions during port operations. Accounting for about 55% of the global total, Asia ports generated the largest container shipping emissions. We compile a list of the top 20 ports in 2015 and 2020 with the greatest emissions and energy consumption (see Supplementary Tables 1 and 2). In 2015 and 2020, except for Rotterdam, all the top ten ports with the highest emissions were in Asia, and five were Chinese ports. Singapore and Shanghai ranked the first and second, and compared with 2015, two Chinese ports, Xiamen and Guangzhou, were added to the 2020 list. Sri Lanka's Colombo port also rose sharply, jumping from 17 in 2015 to 9 in 2020.

The growth of trade demand is the main driver for emission increase in these ports. Asia is abundant in natural resources and dominates global maritime trade, accounting for 41% of all commodities loaded in 2020⁴¹. Additionally, with the removal of intra-regional trade barriers and the construction of port infrastructure, the status and the importance of the above ports have enhanced, which also explains the increase in carbon emissions⁴². Global maritime container shipping emissions in European ports are also significant, with five European ports included in the list in 2015 and 2020, respectively. Two Dutch ports, Rotterdam and Moerdijk, were made to the list in 2020, with Moerdijk being a new port in the 2020 list. Economic growth and trade demand could also tell the story of increased emissions of maritime container shipping (Supplementary Table 3).

Table 1. Descriptions of designed scenarios.

Scenarios	Scenario description
SSP1-ER	The global economy is on a sustainable path, and the maritime industry adopts an aggressive emissions reduction program in order to reach peak container shipping emissions by 2030.
SSP1-EER	The overall global economic development follows a sustainable route and the maritime industry implements a comprehensive decarbonization pathway to target a more than 50% decrease in container shipping emissions in 2050 compared to 2020.
SSP1-SER	The global economy is on a sustainable route, with the maritime industry following a stringent decarbonization path with the objective of lowering emissions from container shipping by more than 90% in 2050 compared to those in 2020.
SSP2-BAU	Global economic growth and carbon reduction trends are projections of what would occur if future policy adjustments, implementation, and enforcement adopt the same patterns as the ones in place today.
SSP5-BAU	The world continues the adoption of a resource- and energy-intensive approach to economic development and intensive exploitation of fossil fuel resources to fuel the maritime industry.
SSP5-ER	The world adopts a resource- and energy-intensive economic development, but the maritime industry implements extra measures to accelerate low-carbon transition.

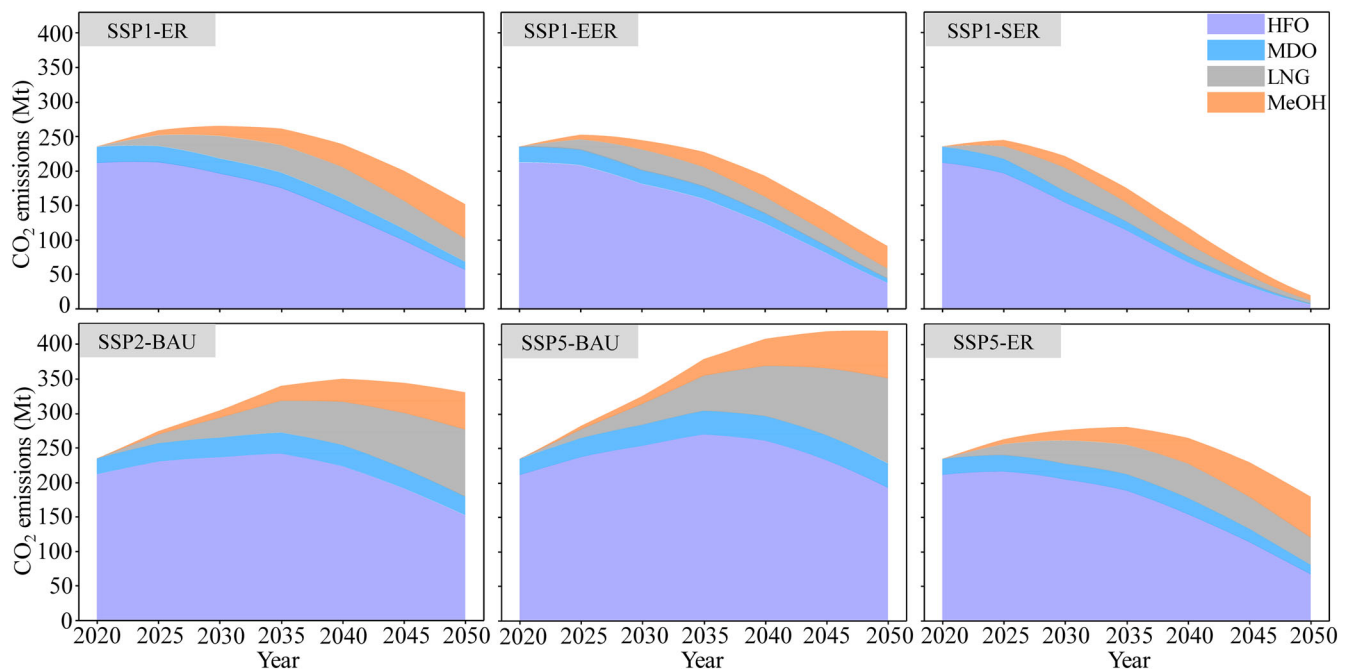


Fig. 4 Projected container shipping emissions across scenarios. Each subfigure depicts the container shipping emissions under a scenario (SSP1-ER, SSP1-EER, SSP1-SER, SSP2-BAU, SSP5-BAU, and SSP5-ER scenarios). Four colors represent carbon emissions from fuel (HFO, MDO, LNG and MeOH) combustion. We assume no carbon emissions from the use of ammonia, electricity, and hydrogen.

This study defines net zero emissions as the absence of any external greenhouse gas offsets and the achievement of net zero emissions in the shipping sector alone. Unfortunately, although emissions under the SSP1-SER scenario are only 19.6 Mt, this scenario still falls short of the 2050 net zero emissions goal due to the significant uncertainties and difficulties in lowering emissions in the transportation sector^{43,44}. Meanwhile, the emission intensity (carbon emissions per unit of GDP) drops progressively in the presence of mitigation efforts, and the intensities in 2050 are 18.5%, 11.2% and 3.56% of the values in the base year under the given SSP1-ER, SSP1-EER and SSP1-SER scenarios, respectively (Supplementary Fig. 6).

In terms of energy usage, there are significant disparities in carbon emission sources under different scenarios. Under the BAU scenario, carbon emissions from HFO combustion dominate the total emissions. Take the SSP5-BAU scenario for example, given the high proportion of HFO in energy mix (Supplementary Fig. 8), HFO combustion contributes 46.0% of the total emissions in 2050, i.e., 193.3 Mt, followed by the adoption of LNG and methanol.

When moving to the EER and SER scenarios, carbon emissions from the burning of HFO and MDO show a decrease trend, as HFO and MDO are gradually replaced by cleaner and less-emission intensified energy. Specifically, the carbon emissions from the combustion of HFO and MDO in 2050 are 43.8 Mt and 7.4 Mt, respectively, under the SSP1-EER and SSP1-SER scenarios; while the share of carbon emissions from the use of LNG and methanol is consistently low, even under the strict SSP1-SER scenario.

Emission reduction contribution analysis

Emission reductions are driven by different factors in terms of short-, medium- and long-term phases. This could be observed from the decomposition of emission reductions under the SSP1 scenarios (Fig. 5), and that under the SSP2-BAU, SSP5-BAU, and SSP5-ER scenarios (Supplementary Fig. 5). In the short run, the trade growth effect dominates the increase in container shipping emissions under the SSP1 scenarios. The effect of energy efficiency improvement can assist control the rise of emissions to some extent, with values of 0.7, 0.67 and 0.65 under the SSP1-ER, SSP1-EER, and SSP1-SER scenarios,

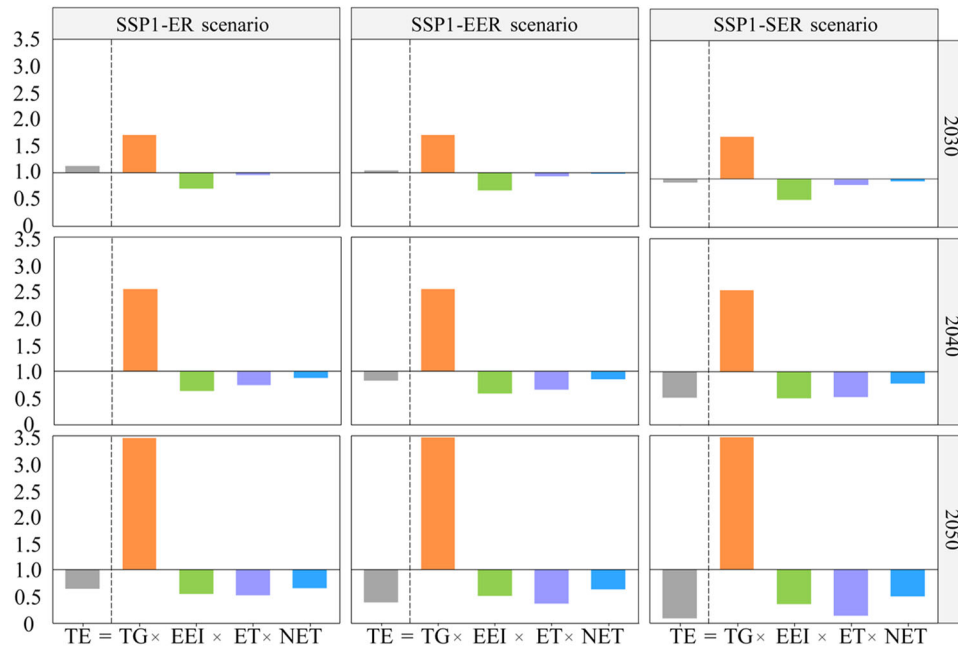


Fig. 5 Emission reduction contributions in the short, medium and long term under the SSP1 scenario. TE is the ratio of total container shipping emissions in different years relative to 2020. TG is short for trade growth, indicating the boosting effect of trade growth on emissions. EEI and ET denote the effect of energy efficiency improvement and energy transformation from fossil fuels to clean fuels, respectively. NET stands for the mitigating effect associated with the use of NETs. TE is the product of these four effects (TG, EEI, ET and NET). The farther the effect value deviates from 1, the greater the impact on total emissions.

respectively. Compared to the contribution of energy efficiency improvement, fuel transition and the adoption of negative emission technologies (NETs) are more challenging to implement in the short term¹⁴. More specifically, the effect of fuel transition does not differ significantly across scenarios, with values of 0.95, 0.94 and 0.9 under the SSP1-ER, SSP1-EER, and SSP1-SER scenarios, respectively. NETs start to play some role in emission reduction only after 2030, and this effect is rather limited, even under the most stringent scenario.

The situation changes when moving to the medium term. Under the SSP1-ER scenario, cumulative trade growth and conservative emission reduction measures result in basically the same emissions as in 2020. As for the SSP1-EER and SSP1-SER scenario, the effects of increased energy efficiency, the switch to zero and low-carbon energy sources, and the adoption of negative emission technologies are more pronounced. As a result, the emission levels in 2040 decrease by 17.9% and 49.7% of the 2020 level, respectively. The greatest contribution to emission reductions comes from the enhancement of energy efficiency, with the effect value of 0.5, followed by the energy transition and the use of NETs. Seen from the long term, carbon emission gap widens among scenarios. The clean energy transformation becomes the dominant mitigation contributor across all targeted scenarios. Meanwhile, NETs also play a significant role in reducing emissions under all SSP1 scenarios.

DISCUSSION

This study proposes an analytic framework by integrating bottom-up accounting of maritime container shipping emissions and upscaling decarbonization projection. The estimation does not show a monotonic trend for global maritime container shipping emissions, and this trend was consistent with the growth of maritime container traffic volume, reflecting that maritime trade demand could be a primary emission driver. With the emergence of regionalization, the emissions per unit of transport distance increased from 0.41 t nm⁻¹ in 2015 to 0.43 t nm⁻¹ in 2020, which underscores the importance of balancing economic growth and

environmental damages. Geographically, we observe a great potential of emission reduction between Asia and Europe, Asia and North America, as well as routes within Asia. As the operational volume of major ports in Asia and Europe continues to grow, improving port operation efficiency has become an important direction for shipping emission reduction in these regions.

Scenario analysis reveals that emissions of the global container shipping industry will not peak until 2040 under all types of BAU scenarios, and HFO combustion contributes the bulk of the total emissions. Under the more stringent scenario (the SSP1-SER scenario), container shipping emissions peak in 2025, with the emission level rapidly fall from the peak (252.4 Mt) to 19.6 Mt by 2050 (accounting for 8.3% of those in 2020), nearing the International Maritime Organization's goal of reaching net zero emissions by or around 2050. Unfortunately, the SSP1-SER scenario falls short of the 2050 net-zero emission goal due to the significant technological uncertainties and difficulties in lowering emissions in the transportation sector. Emission reduction drivers changes significantly over time periods. Energy efficiency improvement performs to be prominent in reducing emission in the short and medium term, and fuel transition acts as the major mitigation contributor, when moving to the long term. Notably, despite a limited role in emission reduction, the use of NETs proves to be indispensable for attaining the IMO goal, especially the enhanced ambition of the coming MEPC 80.

METHODS

Bottom-up estimation of the shipping emissions

The historical container shipping service line data covers 11011 pieces of shipping line records from 2015 to 2020. For each service line, a list of ports that a container ship consecutively calls during the service is provided. The service line data also provides information including service duration, service frequency, traffic capacity, ship types, etc. Based on the above information, this

paper establishes an activity-based method to calculate global container shipping emissions.

A voyage is the process by which a container ship departs from one port to the next. For each voyage on a service line, container ships may experience different operational modes, and these different operational modes can be distinguished with each other by container ships' speed and distance from ports. In this paper, container ships' operational modes on a voyage are divided into three stages, including cruising, manoeuvring and berthing^{1,21}. The annual emission value for each service line is calculated by Eq. (1):

$$E_{service} = E_{cruising} + E_{manoeuvring} + E_{berthing} \quad (1)$$

where, $E_{service}$ is the annual emissions on a voyage, $E_{cruising}$ is the service route's annual emissions during cruising, $E_{manoeuvring}$ is the service route's annual emissions during manoeuvring, and $E_{berthing}$ is the service route's annual emissions during berthing. In this paper, we refer to emissions generated during manoeuvring and berthing as emissions in port, and we refer to emissions generated during cruising as emissions at sea. For each port on a certain service line, the containership's emissions at that port are obtained by distributing the total emissions during manoeuvring and hoteling equally to each transit port on a service line.

This paper assumes that each container ship has one propulsion engine, one auxiliary engine and one boiler. Only propulsion engine and auxiliary engine working during containerships are cruising at sea, and only auxiliary engine and boiler working during containerships are berthing in ports. All three engines work during manoeuvring modes¹. Thus, the service route's annual emissions during cruising/manoeuvring/berthing can be calculated by Eqs. (2)–(4):

$$E_{cruising} = (E_{propulsion} + E_{auxiliary}) \times AC \quad (2)$$

$$E_{berthing} = (E_{auxiliary} + E_{boiler}) \times AC \quad (3)$$

$$E_{manoeuvring} = (E_{propulsion} + E_{auxiliary} + E_{boiler}) \times AC \quad (4)$$

where, $E_{propulsion}$ is the emissions produced by propulsion engine, $E_{auxiliary}$ is the emissions from auxiliary engine, $E_{berthing}$ is the emissions from berthing, and E_{boiler} is the emissions from boilers. AC is the number of services provided by the service route per year, which depends on the departure interval of each service route.

Container ships' emissions depend on engine types, time spent in different operational modes, and emission factors^{21,24,45}.

The Eq. (5) describes the method for calculating emissions produced by propulsion engines.

$$E_{propulsion} = I_{propulsion} \times LF \times \varepsilon_p \times EF_{propulsion,i,j} \times T_j \quad (5)$$

where, $I_{propulsion}$ is the installed power of propulsion engine, which varies with containerships' carrying capacity. Load factor is the ratio between the engine's output power to its Maximum Continuous Rating (MCR) (Ship Business, <http://shipsbusiness.com/engine-load-management.html>). ε_p is the ratio of MCR to main engine's install power, which is assumed to be equal to 0.9¹. $EF_{propulsion,i,j}$ are emission factors, which are constant for a certain kind of pollutant i on one working condition j . T_j is propulsion engine's active time during condition j .

$$LF = \left(\frac{V_a}{MDS} \right)^3 \quad (6)$$

where V_a is the average cruising speed of each service route, MDS is the maximum design speed of containership on each service route, which is determined by the standard ship's maximum carrying capacity on each route. The values of $I_{propulsion}$, V_a and MDS utilized in this paper are derived from the fourth IMO GHGs study (Supplementary Table 7).

The Eqs. (7) and (8) describe the method for calculating emissions produced by auxiliary engines and boilers.

$$E_{auxiliary} = P_{auxiliary} \times EF_{auxiliary,i,j} \times T_j \quad (7)$$

where, $P_{auxiliary}$ is the output power of auxiliary engine. $EF_{auxiliary,i,j}$ are emission factors of auxiliary engines, which are constant for a certain kind of pollutant i on a working condition j . T_j is auxiliary engine's active duration during condition j .

$$E_{boiler} = P_{boiler} \times EF_{boiler,i,j} \times T_j \quad (8)$$

where, P_{boiler} is the output power of boiler. $EF_{boiler,i,j}$ are emission factors of boiler, which are constant for a certain kind of pollutant i on a working condition j . T_j is auxiliary engine's active duration during condition j . The output power of auxiliary engines and boilers are derived from the statistical data from the IMO (Supplementary Table 8).

The method for determining working duration during different operational modes (T_j) is illustrated by Eqs. (9) and (10).

$$T_{cruising} = \frac{D}{V_a} \quad (9)$$

$$T_{berthing} = T_{total} - T_{cruising} - T_{manoeuvring} \quad (10)$$

where, $T_{cruising}$, $T_{berthing}$, and $T_{manoeuvring}$ are working duration of cruising, berthing, and manoeuvring. D is the traveling distance at sea of each service route, and T_{total} is the total duration of each service route. This paper assumes that $T_{manoeuvring}$ for containerships' every port call is fixed to 1 hour⁴⁶.

Emission factors represent the value of pollutants produced by each unit of energy consumption, which vary based on engine types and fuel types. Based on previous studies, we assume that all ships use HFO (Heavy Fuel Oil) for economic advantage during cruising at sea, and all ships use MDO (Marine Diesel Oil) during berthing and manoeuvring to meet emission control policy^{1,8,21}. Emission factors of different engines under different operational modes are obtained based on statistical data from the fourth IMO GHGs study (Supplementary Table 9).

As illustrated in Eq. (11), the total annual emissions are obtained by summing up the annual emissions of each service.

$$E_m = \sum_{i=1}^n E_{service,i} \quad (11)$$

where, E_m is the total CO_2 emissions in year m , n is the number of service routes.

The equation for fuel consumption estimation can be obtained by changing the Emission Factor (EF) in shipping emission estimation equation into Specific Fuel Consumption (SFC). SFC for different engines under different operational modes is derived from the fourth IMO GHGs study report (Supplementary Table 10). This paper assumes that containerships use Heavy Fuel Oil (HFO) during cruising and Marine Diesel Oil (MDO) during manoeuvring and berthing. The energy density assumption is derived from the fourth IMO GHGs study, while $HFO = 40200 \text{ kJ kg}^{-1}$, $MDO = 42700 \text{ kJ kg}^{-1}$, the weight of MDO can be converted to the weight of HFO by multiplying by 0.94.

Global trade is projected on logistic models under all scenarios, and the model is set as follows (see Supplementary Note 2 for more details):

$$x = \frac{1}{1 + \exp(a + bt)} \quad (12)$$

where x is the ratio of global trade divided by GDP and t is time in years and from 1960 onwards, t increases continuously from 0. We use global trade and GDP data from 1960–2020 to estimate the coefficients of a and b . Historical trade data is from the United Nations Conference on Trade and Development and GDP data is from the World Bank. We obtain the per-period GDP projections

from IIASA database for the three SSP scenarios (i.e., SSP1, SSP2 and SSP5) and linearly interpolate every five years to obtain GDP projections for each year from now to 2050.

Modeling the emission reduction pathways

The upscaling pathway analysis method of the proposed BEEPA is based on the Long-range Energy Alternatives Planning System (LEAP), which is an integrated modeling tool developed by the Stockholm Environment Institute (SEI) for scenario analysis. It can be used for short- to long-term emission projections⁴⁷ and is suitable for describing multiple policy scenarios^{48,49}. As a result, the LEAP model has been used in many countries and regions around the world to assess policy effectiveness for single sector and multi sectors^{50,51}.

Scenario settings

Based on the Shared Socioeconomic Pathways and the emission reduction pathways, we define six scenarios (see Supplementary Fig. 3 for details). Firstly, we use global GDP under three SSP scenarios (SSP1, SSP2 and SSP5) to project the trade volume of the corresponding scenarios (Supplementary Note 2). Secondly, the emission reduction pathways consider uncertainties in the reduction of energy intensity, the transformation of the energy mix, and the diffusion of negative emission technologies in the short term (from now to 2030), the medium term (2031–2040) and the long term (2041–2050)¹⁴. Four emission reduction scenarios are designed based on emission reduction intensity, namely, BAU, ER, EER and SER. Lastly, the coupling of trade growth and emission reduction needs to take achievability into account. On the one hand, large-scale energy substitution and technological upgrading necessitate substantial infrastructure development and investment⁵², which will inevitably have an impact on economic growth. On the other hand, high economic growth is likely to remain the heavy dependence on fossil fuel use for decades to come, potentially crowding out investment in emissions reductions⁵³. Therefore, we denote the six scenarios as the SSP1-ER, SSP1-EER, SSP1-SER, SSP2-BAU, SSP5-BAU, and SSP5-ER (Supplementary Note 3). Future technological change is highly uncertain, and while our scenario setting enables discussion of the uncertainty of trade growth and energy transition pathways, the timing of technology adoption, cost effectiveness, and other issues are not explored further due to data limitations^{54,55}.

DATA AVAILABILITY

The historical container shipping service line data utilized in this paper is derived from Alphaliner (<http://www.alphaliner.com/>), with the data covering 98% of the world's container liner service lines. Historical trade data is from the United Nations Conference on Trade and Development (<https://unctadstat.unctad.org/wds/ReportFolders/reportFolders.aspx>) and GDP data is from the World Bank (<https://data.worldbank.org/indicator/NY.GDP.MKTP.CD>). We obtain GDP projections from IIASA for the three SSP scenarios (SSP1, SSP2 and SSP5) and linearly interpolate every five years to obtain GDP projections for each year from now to 2050.

CODE AVAILABILITY

Code used in calculation of this study is available from the corresponding author upon request.

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COMPETING INTERESTS

The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to Hongbo Duan.

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